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UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES DEPT OF
AEROSPACE ENGINEERING R BLACKWELDER ET AL. 26 JUN 87

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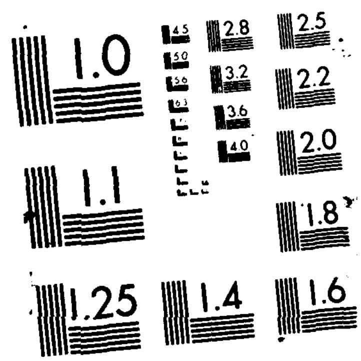
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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

EXPERIMENTAL AND THEORETICAL EFFORTS AIMED AT CLARIFYING AND REVEALING IMPORTANT DYNAMICAL FEATURES OF SEVERAL TURBULENT SHEAR FLOWS ARE DESCRIBED. THE FLOWS STUDIED INCLUDE BOUNDARY LAYERS, JETS, WAKES AND SEPARATED FLOWS ON LIFTING SURFACES. SIGNIFICANT PROGRESS HAS BEEN MADE THROUGH EXPERIMENTAL STUDIES TOWARD UNDERSTANDING: i) PROCESSES IN TURBULENT BOUNDARY LAYERS RESPONSIBLE FOR THE PRODUCTION OF TURBULENT ENERGY VIA LOCAL, INFLECTIONAL-INSTABILTY EVENTS AND THE MODIFICATION OF BOUNDARY LAYER GROWTH AND ENTRAINMENT BY PASSIVE, LARGE-EDDY MANIPULATION DEVICES; ii) PROCEDURES FOR ENHANCING ENTRAINMENT AND MIXING IN JETS EITHER BY ACTIVELY FORCING THE FLOW OR BY PASSIVELY CONTOURING THE JET EXIT; AND iii) CHARACTERISTICS OF BOUNDARY LAYER SEPARATION AND ITS CONTROL ON LIFTING SURFACES IN UNSTEADY FLOWS. THEORETICAL STUDIES ON THE TEMPORAL AND SPATIAL STRUCTURE IN BLUNT-BODY WAKES HAVE REVEALED THE NECESSARY CONDITIONS UNDER WHICH GLOBAL, SELF-SUSTAINED OSCILLATIONS APPEAR AND, ALSO, HAVE PROVIDED FIRM CRITERIA FOR SPECIFYING THE FREQUENCY OF THESE OSCILLATIONS. THE RESULTS ARE CONSISTENT WITH EXISTING EXPERIMENTAL EVIDENCE AND SUGGEST PROMISING APPROACHES FOR DRAG MODIFICATION FOR FLOW OVER BLUFF BODIES. SEVERAL EXPERIMENTAL FACILITIES HAVE BEEN DESIGNED.

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ANNUAL TECHNICAL REPORT

AFOSR Contract No. F49620-85-C-0080

May 1, 1986 - April 30, 1987

TASK I: STUDIES OF UNSTEADINESS IN BOUNDARY LAYERS

Co-Principal Investigators: Ron Blackwelder and R.E. Kaplan

OBJECTIVES

Develop an adverse pressure gradient in the Low Turbulence Wind Tunnel in preparation for a study of the bursting process on equilibrium boundary layers.

Construct and test a new hot-wire probe that can sense and make corrections for reversing flow fields near a solid boundary.

Modify the turbulent eddies on the outer region of a boundary layer and study the effect on entrainment and growth of the layer.

Study the local inflectional velocity profiles in a turbulent boundary layer and measure the shear amplitude and other characteristics related to an inviscid instability mechanism.

Set up an unsteady disturbance in a flow field that models the turbulent wall eddies and study the interaction between the disturbance and the breakdown of the wall structure.

STATUS & RESULTS OF RESEARCH

• The low Turbulence Wind Tunnel has been renovated and modified during the past year. A new traverse had to be designed and installed to accomodate the reconfiguration of the tunnel's test section. The new three-dimensional traverse is fully automated and can access any location in the test section via computer control. Fortran callable programs have been developed so that complete data runs, such as a set of boundary layer profiles, can be obtained automatically without operator intervention.

Since the wind tunnel serves several experiments simultaneously, it would have been inconvenient and awkward to use inserts or adjustable walls to attach the desired pressure gradients. A new technique has been utilized in the 2' X 3' test section which employs suction or blowing through a porous wall in the wind tunnel. Over 60% of one of the 3' side walls has been replaced with a porous metallic surface. Three separate individual plenums have been installed behind the porous wall outside the test section. Each plenum has a separate fan for controlling the velocity flow through the plenum. Local control of the pressure gradient is achieved by covering portions of the porous surface with tape. Thus by controlling the volume flow through each plenum, a tailored pressure gradient can be obtained in the test section. This method has the advantage that the wind tunnel can also be used for zero pressure gradient studies by turning off the plenum fans.

The boundary layer under study develops on a flat plate located near the opposite 3' side wall. To date, an equilibrium adverse pressure gradient has been obtained that has the same non-dimensional strength as those obtained by Clauser (1954, J. Aero. Sci., 21, 91) and Bradshaw (1967, JFM, 29, 625). The advantage of the present flow is that the wall region is sufficiently thick that detailed measurement can be obtained there. A series of boundary layer profiles have been taken along the streamwise coordinate on the test section and an excellent collapse of the data obtained, thus indicating that a good equilibrium layer has been obtained. Measurements of the bursting phenomenon and associated eddy structure is presently beginning.

• Hot-wire anemometers have primarily been limited to measuring velocity magnitude since they cannot sense the flow direction. The only exception has been the pulse-wire anemometer; however, the associated circuitry and signal processing has made this configuration difficult to implement. A new sensor has been developed in anticipation of making measurements in a strong adverse gradient boundary layer with reversing flow. The probe employs a single constant-temperature hot-wire probe as the central element whose output signal yields the velocity magnitude. Two constant current hot-wire sensors are positioned directly 0.3 mm upstream and downstream of the central probe. These two sensors are operated at low overheat so that they sense only the temperature. Consequently they are used to determine the direction of the wake from the central hot-wire and thus the direction of the flow field.

The probe has been tested in a specially constructed calibration flow facility capable of producing a mean and oscillating flow field with frequencies up to 400 HZ. An algorithm has been developed to correctly determine the flow direction for all frequencies up to 400 HZ with amplitudes exceeding 1 m/sec with and without a mean flow. The development of this instrument has been completed and will be reported at the ASME Thermal Symposium in June, 87.

• The modifications of the turbulent boundary layer by LEBU devices and the ensuing study of the entrainment has been completed. This novel study used heat as a passive contaminant to study the effects of the LEBUs on the growth of the turbulent boundary layer. Heat was added by individual heaters consisting of a nichrome wire placed at different locations in the flow field and by heating the entire wall of the boundary layer. Correlation measurements, conditional averages and other statistics indicate that the primary effect of the LEBU's is to alter the entrainment of irrotational fluid into the boundary layer. The interfacial region becomes less corrogated with the LEBU's installed and the velocity fluctuations are correspondingly decreased. The temperature fluctuations are strongly decreased due to the inhibited mixing.

Any drag reduction associated with the LEBU's seems to be due to the fact that the entrainment is decreased and hence the boundary layer grows at a slower rate until it recovers far downstream.

• Detailed studies of the turbulent boundary layer at USC and elsewhere have shown that instantaneous inflectional velocity profiles exist ubiquitously throughout the flow. Using instantaneous velocity data in the normal and spanwise directions, the frequency of occurrence of inflection points has been studied. Since these profiles may lead to inflectional instabilities and subsequent production of turbulent energy, the characteristic parameters related to the instability have been measured. For example, histograms of the growth rate of the instabilities suggest that they grow explosively; i.e. the amplitude increases by a factor of 1000 while travelling only 300 ν/u_τ downstream. This work is continuing and will be supplemented by numerical simulated turbulence data in the near future.

• The wind tunnel used to emulate turbulent boundary layer wall structure (i.e. the Gortler Wind Tunnel) had to be disassembled and stored during this past year while the new laboratory facilities were constructed. The wind tunnel has been restored to operation and is being instrumented to study the effects of an unsteady perturbation on the wall structure.

PROFESSIONAL PERSONNEL

Dr. R.F. Blackwelder, Professor, Dept. of Aerospace Engineering, USC, Co-PI.

Dr. R.E. Kaplan, Professor, Dept. of Aerospace Engineering, USC, Co-PI.

Mr. S.I. Chang, Research Assistant, Dept. of Aerospace Engineering, USC.

Mr. I. McLean, Research Assistant, Dept. of Aerospace Engineering, USC.

Mr. J. Roon, Research Assistant, Dept. of Aerospace Engineering, USC.

INVITED TALKS

Presented five seminars as recipient of the "Distinguished Lectureship in Fluid Dynamics" at University of Texas, Austin, February 2-6, 1987.

* "Dynamics of Large Scale Eddies in Turbulent Wall Layers"
* "The Bursting Process"
* "Analogies Between Transitional Boundary Layers and the Bursting Process"
* "Perturbations of Turbulent Boundary Layers"
* "Turbulent Boundary Layers - A Fertile Research Area"

PUBLICATIONS

1) "The Growth and Breakdown of Streamwise Vortices in the Presence of a Wall" J.D. Swearingen and Ron F. Blackwelder, accepted for publication in Journal of Fluid Mechanics.

2) "A Hot-Wire Probe for Velocity Measurement in Reverse Flow" Ron F. Blackwelder and Ian McLean, accepted for publication by ASME.

3) "On the Spacing of Streamwise Vortices on Concave Walls" J.D. Swearingen and Ron F. Blackwelder, AIAA Journal, 24, 1706, 1986.

4) "Length Scales & Correlations in LEBU Modified Turbulent Boundary Layers" Ron F. Blackwelder and Shi-Ing Chang, AIAA 24th Aerospace Sciences Meeting, AIAA-86-0287, 1986.

5) "On the Structure of Turbulent Spots in a Heated Laminar Boundary Layer" E. Gutmark and Ron F. Blackwelder, Experiments in Fluids, 5, 217, 1987.

6) "Large Eddy Modification in a Turbulent Boundary Layer" Shi-Ing Chang and Ron F. Blackwelder, Bull, Am. Phys. Soc., 31, 1703, 1986.

TASK II: UNSTEADY SEPARATION AND UNSTEADY SHEAR LAYERS

Principal Investigator: Ho, Chih-Ming

OBJECTIVES

Free shear layers are common in chemical reacting devices and in separated flows. A basic understanding of the dynamics could lead to the proper control of the evolution of the flow and to the better performance of separated airfoils. In this study, we investigate both the passive control of an asymmetric jet and the active control of a two-dimensional jet. The information gathered from the experiments has been applied to controlling the unsteady separation on 2-D airfoils and to improving combustion efficiency.

STATUS OF RESEARCH EFFORT

1. Elliptic Jet

We have demonstrated that the entrainment of a small aspect ratio elliptic jet can be ten times higher than that of a 2-D jet. This year, we have finalized the design of an active forcing device which is able to provide variable forcing levels and phase in the azimuthal direction. The blower was replaced by a more powerful one and was able to increase the velocity from 20 m/sec to 75 m/sec. Furthermore, we now have a new nozzle made of graphite material which can withstand heat of 250° C. A heater which is able to heat the flow up to 200° at maximum speed was installed. After many trial and error tests, the elliptic jet has finally achieved uniform velocity and temperature distributions.

With these extended capabilities of the jet, we will be able to examine the effects of forcing and heating on the growth of the 3-D jet. A heated jet is a more realistic simulation of the practical application and very few basic studies have been available in the last decade. We anticipate interesting results in the near future.

2. A Plane Jet

Last year, we used two extension plates to make the plane jet bi-stable and obtained a 45° spreading angle. At present, we find that the growth of the jet can be greatly increased by using out-of-phase forcing at the nozzle exit and eliminating the extension plates. The entrainment is about three times higher than that of an unforced jet. The most interesting point is that large mass transfer is caused by a low frequency perturbation. The perturbation frequency is more than one magnitude lower than the forcing frequency and is identified to be inherent to the flow. The nature of this disturbance is not clear at present and its clarification is important not only to the manipulation of entrainment but also to the global control aspect of the plane jet.

UNSTEADY AERODYNAMICS

OBJECTIVES

The purpose of studying unsteady aerodynamics is to understand the fundamental aspects of unsteady separation, so that the performance of aircraft under post-stall maneuvering can be enhanced. We examined the responses of both 2-D and delta wings placed in unsteady free streams.

A unique water channel was built and is able to provide unsteady free stream velocities in accelerating and decelerating cycles. By using a computer controlled gate, we are able to trim the velocity to a wide variety of desired forms With this flexibility, the unsteady aerodynamic properties can be examined in great depth.

STATUS OF RESEARCH EFFORT

1. Control of 2-D Wing

The NACA 0012 wing experienced global separation during the deceleration phase and attached flow in the acceleration phase. An unsteady shear layer originated whenever the leading edge separation bubble burst at the end of the acceleration period. By placing a small flap at the origin of the shear layer and oscillating at a specific phase difference from the free stream variation, the separated zone could be reduced in size. The lift and drag are expected to be changed by this effective control technique.

2. A Delta Wing in Unsteady Flow

The flow visualization and lift measurements were carried out for a delta wing in accelerating and decelerating flows. When the unsteady flow had 1 Hz frequency, the pressure gradient was equivalent to the wing subjected to a 10 G acceleration or deceleration in air. The visualization did not show a significant change of the leading edge separation vortices and the time averaged lift coefficients were not different from the static values. These results imply that the leading edge vortex pairs are very "robust". The phase averaged lift followed the time derivative of the free stream velocity component normal to the wing. Hence, the additional lift is produced by the inertia of the unsteady fluid.

PROFESSIONAL PERSONNEL

Dr. Ho, Chih-Ming - Principal Investigator

Dr. Mario Lee - Research Associate, responsible for the investigation of the delta wing and building the new unsteady water channel

Mr. Chiang Shih - Research Assistant, responsible for the study of the control of the 2-D airfoil

Mr. Thomas Austin - Research Assistant, responsible for the study of the elliptic jet

Mr. Mike Zabat - Teaching Assistant, only supported in the 1986 summer and responsible for the investigation of the plane jet

CONSULTING FUNCTION

1. Naval Weapons Center
   Subject: Ramjet with asymmetric nozzle
   Personnel: Drs. K. Schadow, E. Gutmark, S. Koshigoe

2. Oakridge National Laboratory
   Subject: Supersonic Ejector
   Personnel: Drs. F. Chen, R. Murphy

3. Flow Research Inc.
   Subject: Asymmetric Ejector
   Personnel: Dr. S. Knoke

INVITED TALKS

1. "Evolution of Coherent Structures and Small Scale Transition in Mixing Layers", Workshop on Computational Fluid Mechanics, Institute of Nonlinear Science, University of California at Davis, Davis, CA July 18, 1986.

2. "Entrainment and Fine Scale Mixing in Free Shear Layers", Southwest Mechanics Lecture Series, 1986.

PUBLICATIONS

1) "Interactions between Large Structures and Small Eddies in a Plane Jet", with Hsiao, F.B. IUTAM Symposium on Fluid Mechanics in the Spirit of G.I. Taylor, 1986.

2) "Aerodynamic Research on Flow Separation and Dynamic Stall: Some Recent Advances" with Cheng, H.K., Aerospace Simulation, ed. M. Ung, pp. 187-198, 1986.

3) "Near Wake of an Unsteady Symmetric Airfoil", with Chen, S.H., To appear in J. of Fluids and Structures, 1986.

4) "Vortex Induction and Mass Entrainment in a Small Aspect Ratio Elliptic Jet", with Gutmark, E. To appear in Journal of Fluid Mechanics, 1987.

5) "Control of Unsteady Separation on Symmetric Airfoils", with Shih, C. and Lee, M., Proc. of IUTAM Symposium on Control of Turbulent Flows, 1987.

6) "Leading Edge Separation over a Delta Wing" with Lee, M. and Shih, C., Accepted by ASME Fluids Engineering Spring Conference, 1987.

7) "Observations of Global Structure in Turbulent Free Shear Flows", with Browand, F.K., 1987.

8) "Unsteady Separation on Elliptic Cylinders", with Shih, C., Bulletin of the American Physical Society, Vol 31, p.1708, 1986.

TASK III: SEARCH FOR CHAOS IN FREE SHEAR FLOWS: THE CASE OF THE WAKE-SHEAR LAYER

Co-Principal Investigators: Patrick Huerre and Larry G. Redekopp

OBJECTIVES

As stated in our last progress report, the project is conducted as a coordinated analytical-numerical-experimental effort involving a team of researchers from USC and

UCLA. The main objectives are:

* determination of frequency selection criteria in mixed flows (absolutely unstable in one region, convectively unstable in another region). The archetype of such flows is the wake or wake-shear layer.

* identification of deterministic chaos, spatial, temporal, or both, in wake-shear layers.

STATUS OF RESEARCH EFFORT

Significant progress has been made in the following areas:

* Theoretical models based on the Ginzburg-Landau equation with varying coefficients have allowed us to show that the existence of a finite region of absolute instability is a necessary condition for the occurrence of global resonances [Chomaz, Huerre, and Redekopp (1986), (1987a) and (1987b)]. These studies also indicate that a solid frequency selection criterion cannot be deduced from local stability conditions alone. It should involve the global problem and its boundary conditions. These analyses considerably clarify the connection between local stability arguments and the onset of self-sustained resonances. The scenario which we have proposed for the onset of the Karman vortex street seems to correlate very well with experimental findings. Detailed stability calculations of wake profiles [Monkewitz (1987)] have firmly established that the wake can be considered as a convectively unstable flow below Re=40 and as a mixed flow above, with a self-sustained resonance regime. Work is under way to pursue the theoretical analysis on a physical model of the Karman vortex street instability. We feel that these concepts can be extremely fruitful in defining a control strategy for wakes behind bluff bodies

* A combined theoretical/numerical investigation is under way to study the interaction between the sinuous and varicose modes in two-dimensional wake-shear layers. We have made significant progress in this areas. A set of evolution equations

$$\frac{dA}{dx} = \sigma_A A + \lambda_A B^2 \tag{1}$$

$$\frac{dB}{dX} = \sigma_B B + \lambda_B A B^* , \tag{2}$$

has been derived to describe the nonlinear coupling between the respective complex amplitudes A and B of tl.ɔ sinuous and varicose modes. The values of the coefficients σ_A and σ_B have been calculated from linear theory. More importantly we have obtained asymptotic estimates of the interaction coefficients in the viscous critical layer limit, when the Reynolds number Re is large and the velocity ratio R is small. It has been established that both λ_A and λ_B are of the form

$$\lambda_A = \Lambda_A \, R Re^{2/3} \quad , \quad \lambda_B = \Lambda_B \, R Re^{2/3} \quad , \quad R << 1 \quad , \quad Re >> 1,$$

where the order one constants Λ_A and Λ_B are known explicitly. Equations (1) and (2) are now being analysed from the nonlinear dynamical systems point of view. We are hopeful that non trivial trajectories in phase space will give rise to a chaotic spatial distribution of vortices.

* The large water channel has now been built and it is being installed in the new Rapp Enginering Building. The spatio-temporal dynamics of the interaction between the sinuous and varicose modes will, in particular, be studied experimentally. The streamwise extent of the facility is such that we will be able to follow the vortical structures far downstream.

PROFESSIONAL PERSONNEL

Dr. P. Huerre, Associate Professor, Dept. of Aerospace Engineering, USC, Co-PI.

Dr. L.G. Redekopp, Professor, Dept. of Aerospace Engineering, USC, Co-PI.

Dr. P.A. Monkewitz, Associate Professor, Dept. of Mech., Aerospace & Nuclear Engineering, UCLA, Consultant.

Dr. J.M. Chomaz, Postdoctoral Research Fellow, Department of Aerospace Engineering, USC.

Mr. J. Sauliere, Research Assistant, Department of Aerospace Engineering, USC.

INVITED TALKS

1) "Hydrodynamic Instabilities in Open Flows: A Bird's Eye View", P. Huerre Workshop on "Propagation in Far from Equilibrium Systems", Les Houches, France, March 11-18, 1987.

2) "Hydrodynamic Resonances, Closed and Open Flows, and Chaos", P. Huerre, Applied Mathematics Working Seminar, University of Arizona, Tucson, October

23, 1986.

PUBLICATIONS

1) Chomaz, J.M., Huerre, P. and Redekopp, L.G. (1986), "Wave Selection Mechanisms in Open Flows", Bulletin of the American Physical Society, Vol. 31, p. 1696.

2) Chomaz, J.M., Huerre, P. and Redekopp, L.G. (1987a), " Models of Hydrodynamic Resonances in Separated Shear Flows", Abstract, Sixth Symposium on Turbulent Shear Flows, Toulouse, France, Sept. 7-9, 1987.

3) Chomaz, J.M., Huerre, P. and Redekopp, L.G. (1987b), "Local and Global Bifurcations in Spatially-Developing Flows", Submitted to Physical Review Letters.

4) Monkewitz, P.A. (1987), "The Absolute and Convective Nature od the Instability in Two-Dimensional Wakes at Low Reynolds Numbers". Submitted to Physics of Fluids.

5) P. Huerre (1986), "Strange Attractors as Models of Turbulence", Proceedings of the "First World Congress on Computational Mechanics", University of Texas, Austin, September 22-26, 1986, Vol. II.

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